INTELLIGENT OPTIMAL CONTROL OF BIOTECHNOLOGICAL PROCESSES

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Abstract The aim of the paper is to present an approach to optimal control of biotechnological processes, described by fuzzy sets which is based on genetic algorithms (GA). It allows more adequate, flexible and *intelligent* (human oriented) description of bioprocess dynamic and inclusion of this information in an effective and robust optimization procedure. Related algorithms and software are designed and tested with data from the real biotechnological process of β-d-glucose-O_2-oxidase-1 synthesis. The proposed approach and algorithms are applicable to other bioprocesses.

1. Introduction

Optimal control of biotechnological processes is very important for their efficiency [2,6,7,18,20]. However, deterministic descriptions which are commonly used, are not full enough and neglect some possible process states [6,7]. Biotechnological processes are characterized by uncertainties, non-quantified factors (such as smell, taste, color, morphophysiological specifics, sediment rate etc.) [22,25]. Practically, for well performance of fermentation processes very important are subjective estimations of the experienced technologist [2,22].

In general, two types of models are used in optimization problems:

i) deterministic models;

ii) *soft* models

The second type of models (*soft* models) includes:

a) fuzzy models;

b) neural-network-based models;

c) expert systems in combinations with a) and b);

As it is known, there exist a number of fuzzy models: fuzzy linguistic models, models with fuzzy parameters, with fuzzy relations etc. There also exist a number of generalizations of the optimal control problem for the case when fuzzy elements exist. However, most of them are practically non-applicable to real problems, because of computational efforts.

There exist a number of generalizations of the optimal control problem for the case when fuzzy elements exist [3,4,17]. However, most of them are practically non-applicable to real problems, because of computational efforts [16,25]. An approach (called FOC) for numerical solving of optimal control problem under fuzziness was proposed by the applicant (3) and was applied to real processes (2,4). Subjective estimated specifics are included into the fuzzy model by choosing the *typical* process duration (*typical* run). This approach is computationally effective, but the derivatives of the respective deterministic model should be known.

In the last decade an alternative tool for optimization have been extensively developed: so called genetic algorithms (GA) [1,8,12,13]. Their application to dynamic optimization and to biotechnological processes just starts. Kacprzyk [9] proposed using of GA for more effective solving a type of fuzzy multistage optimization problem [10,11]. GA are applied to the coded problem directly: simultaneous backward and forward computations are avoided, expression of the model (transition function) and its derivatives is not necessary. However, this approach is not applied to optimal control of bioprocesses.

Rivera and Karim [19] used a variant of GA (so called micro GA for dynamic optimization of bioprocesses applying it to a neural-network-based model of ethanol production by the strain *Zymomonas mobilis* [18]. However, the neural network is applied directly to the data. It would be more respective to the specifics of the bioprocess to use some neural-network based models (for each phase of the process) and to use qualitative information (concerning smell, taste, color etc.) which could be represented by fuzzy linguistic variables.

2 Intelligent Optimal Control Approach

It is proposed to combine the advantages of the FOC approach and of GA and to design a new approach: **I**ntelligent **O**ptimal **C**ontrol (**IOC**). It would be more respective to the object (real bioprocess) then the approach used in [19] because the model of the process could be represented by fuzzy sets. It would be also more easy and more effective than FOC because derivatives can be unknown *a priory* and because GA are robust to the problem. Applying IOC approach to a bioprocess it will be possible to describe each element of the dynamic optimization problem by fuzzy sets:

a) objective function. More respective to the real problem formulation can be used, e.g. “enzyme activity at the end of the process to be *if possible* higher than 100[U/ml]”.

b) transition function. The process dynamic can be represent by the following *soft* model using fuzzy equations: The highest priority is given to the values of the state vector which are respective to the *typical* process duration (subjectively determined process run taking into account qualitative information). The lowest priority is given to the values of the state vector which are determined by the deterministic model. Using of fuzzy linguistic model for description of process dynamics will be investigated. This type of models is less appropriate for dynamic optimization when *classical* approaches (gradient methods, Pontryagin's maximum principle and dynamic programming method) are applied because of cumbersome computations. However, it could be useful when GA is used.

c) transversality condition. Fuzzy transversality condition "Substrate concentration at the end of the process to be *if possible* zero" is more realistic because full utilizing of the substrate is an idealization.

It is proposed an appropriate modification of GA to be applied for solving such FOC problem which can be sketched in computer code as:

begin
k := 0
set the initial population $\Pi(k)$ which constitutes of randomly generated strings of fuzzy controls (agitation rate, RPM);
for each RPM_0, RPM_1,..., RPM_{N-1} in each population $\Pi(k)$,
find the resulting concentrations of cell mass (X_{k+1}), substratum (S_{k+1}) and enzyme activity,(A_{k+1}) and evaluate each string in $\Pi(k)$
while k<N do:
begin
k := k+1
assign the probabilities to each string in $\Pi(k-1)$ which are proportional to the value of the evaluation function for each string and randomly (applying this probabilities) generate the new population $\Pi(k)$
perform crossovering and mutation on the strings in $\Pi(k)$
calculate the evaluation function for each string of $\Pi(k)$
end
end.

In the full variant of the paper a test example and an comparative analysis will be made.

3 Relevant Literature

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